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New tools, new thinking: Biomimetic Process Design through Parametric Modelling and Simulation

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ABSTRACT

This paper examines the mutually beneficial relationship between biomimetics and modelling and simulation tools, showing how each can enhance the other. Through a literature review and a detailed use case on anaerobic digestion, the study highlights how the complexity, multiscale organisation, and functional richness of biological systems challenge current modelling capabilities. By analysing the contributions of modelling and simulation to product development, such as early performance validation, rapid and low-cost iteration, and multicriteria evaluation, the paper questions whether integrating modelling and simulation tools to biomimetics would bring similar benefits to the design process. Several hypotheses are formulated regarding the potential contributions of modelling and simulation to biomimetics, particularly the improvement of biological system understanding through advanced visualisation and the assessment of functional viability using parametric modelling. Integrating such tools into biomimetics is envisioned as a means to reinforce the existing methodology, support more reliable principle transfer, and facilitate the wider adoption of biomimetics as a problem-solving design approach, ultimately promoting the emergence of biomimetic innovations across diverse applications.

Keywords: Biosystems, Modelling and Simulations, Multiscale Modelling, Process Design, Natural Gas

INTRODUCTION

The integration of modelling and simulation tools into product design and development processes has been widely recognized as a key enabler of reduced time-to-market, increased product complexity, and early validation of performance, safety, and fault tolerance [1]. Simulations allow engineers to rapidly and accurately understand physical behaviours before building physical prototypes, supporting a "learn-before-doing" approach that enhances design efficiency [2]. Beyond accelerating learning, simulation-based approaches enable designers to consider technological, economic, and logistic criteria in parallel, helping identify feasible design alternatives and suitable process plans [3]. Such tools support the design of complex, multidisciplinary systems, facilitate experimentation with technology integration, reduce physical prototyping costs, and promote collaboration among engineering teams [2, 4].

Recent decades have witnessed exponential growth in both numerical computational capabilities and advanced manufacturing technologies. Indeed, the improvements in computing power led to strong progression in the capacity to simulate, model, and forecast intricate systems and processes [5]. Manufacturing technologies have evolved from primarily subtractive processes to include sophisticated additive techniques capable of producing geometries with internal features, gradient materials, and hierarchical structures, previously impossible to fabricate [6]. This convergence of computational and manufacturing capabilities seems to have induced a shift in engineering design, from "what can do" to "what should we do" [7]. In other words, from "what can we feasibly produce given our constraints?" to "what should we create to best meet our objectives?". Technological ceilings have been pushed further, thus opening the door to design spaces that were previously inaccessible. A next step could be in the remoulding of design approaches from the current top-down approach to a bottom-up one, so true hierarchical structural design of multifunctional materials and products could be achieved. The bottom-up approach is notably observed in nature and living systems. There is a design process, named biomimetics, that is the practice of mimicking biological strategies to fix practical problems in human activities (ISO 18458:2015). Biomimetics offers a compelling framework for the development and improvement of modelling and simulation tools, as biological organisms embody complex, multiscale, and multifunctional systems, difficult to replicate or to model accurately [5, 8].

Drawing on both a literature review and the analysis of a use case on anaerobic digestion, this work aims to highlight the mutually beneficial relationship between modelling and simulation tools and biomimetics. The objective is twofold: first, to explain how biomimetics can drive advancements in modelling and simulation; and second, to explore how these tools, in turn, can enhance the biomimetic design process. To address this objective, the first part outlines the biomimetic approach and summarises its relevance supported by literature for modelling and simulation tools. The second part introduces the anaerobic digestion use case, which examines the relevance in a practical context.

STATE OF THE ART

Biomimetics, a branch of design

Biomimetics, or bio-inspired design (BID) is a subset of design sciences, from which it borrows its procedural structure. Two methodological paradigms predominate in BID. The first, known as 'problem-driven', begins with the identification of opportunities and needs. The aim is to search for solutions to a specific technical problem in the living world. The second, known as 'solution-based', starts from an already identified biological mechanism for which potential technical applications are sought [9].

To illustrate this methodological dichotomy, the example of aerodynamic devices at the tips of aeroplane wings (winglets) can be considered. Inspired by the flexible feathers of large birds of prey, these elements significantly reduce the aerodynamic drag of the aircraft, thereby optimising its performance and reducing its energy consumption. This innovation perfectly exemplifies the 'problem-driven' approach, where a specific technical issue has guided research towards an analogous biological solution. Conversely, the mechanism by which burdock seeds attach themselves illustrates the 'solution-based' approach. This plant, commonly found in meadows, uses zoochory as a dispersal strategy, exploiting the passage of animals to passively transport its seeds to new territories. The characteristic hooks on these seeds allow them to adhere effectively to the fur of wildlife, while detaching easily during grooming activities. Georges de Mestral, the inventor of Velcro was inspired by this simple and repeatable hook-and-loop principle to develop a revolutionary fastening system, initially applied to the footwear industry, which has since become a universally adopted product.

These two design pathways are formalised in BID, they answer different stakes, but in themselves are not superior to one another [10].

Methodological approaches developed

The scientific community has developed various methodological approaches to guide and facilitate the biomimetic process. Zhang identifies three distinct phases in the evolution of these solutions [11]. The first focused on developing generic tools to facilitate the transition between biological and technical fields. The second phase focused on the development of processes and guidelines encompassing the entire biomimetic approach. A third, more contemporary phase focuses on the evolution towards integrated data platforms, with or without the incorporation of artificial intelligence technologies.

The growing interest in integrating advanced digital technologies into biomimetics (digital imaging, parametric design, artificial intelligence…) stems from their ability to facilitate the analysis, emulation, and optimisation of biological structures [12]. The incorporation of these technologies allows iterative feedback loops to be established between the different phases of biomimetic design, simultaneously enriching the design process and the definition of manufacturing requirements [12].

Biomimetics as a North star

As technological constraints diminish and design possibilities expand, engineering requires guiding principles to direct innovation efforts productively [7]. Biomimetics offers a compelling framework for this purpose.

Biological organisms represent the outcomes of billions of years of evolutionary optimization and adaptability under real-world fluctuating constraints including material availability, energy efficiency, and environmental compatibility [5]. Living systems exhibit remarkable properties achieved through hierarchical structuring, multiscale optimization, and efficient use of available materials [12]. Spider silk, for example, achieves extraordinary tensile strength and toughness through a hierarchical protein structure spanning from the molecular to the fibre scale, with mechanical properties rivalling synthetic high-performance materials despite being produced at ambient temperature and pressure using aqueous processing [13]. This biological example presents both inspiration and technical challenges for engineers. The complexity, multiscale nature, and multifunctionality inherent in biological systems make them difficult to model accurately with computational tools and challenging to replicate with existing manufacturing processes [8, 14]. However, this difficulty aligns well with the need for ambitious targets that push technological capabilities forward. Biomimetics could thus provide direction for innovation efforts through modelling, simulation and manufacturing, which would stimulate the development of new tools and upgrades [11].

By essence, biomimetics is an interdisciplinary approach. Its integration to modelling and simulation tools would foster the crossing and collaboration of domains, which has been identified as a success factor [15]. Integrating biomimetics to modelling and simulation tools is an opportunity to broaden the problem-solving mindset of engineers [9]. Living principles differ from engineering ones, and so, looking at a problem through a biomimetics lens can sometimes shift perspective and possible solutions on said problem [16].

Another addition to the relevance of biomimetics as a north star for future development in modeling and simulation, is that through biomimetic design, the notions of sustainability, resource efficiency, and environmental compatibility can be accounted for [17]. This is encompassed in the broader term of biomimicry. By essence, a biomimetic product is not intentionally sustainable, but the design process is highly compatible with the inclusion of such factors [18]. This inclusion integrates biomimetic design in the demands set by societal objectives for the environmental transition.

Therefore, biomimetics is an opportunity for the modelling and simulation community to profit from the newly acquired capacities of their tools, and challenge them with the ability to model complex, multiscale, multifunctional systems. Biomimetics also brings an input of interdisciplinarity, and fits well with the consideration of sustainability factors, both essential elements in product design and development.

MATERIALS AND METHODS

Building on the arguments put forward by the literature in favour of biomimetics for modelling and simulation tools, a use case was set up. The following section presents the materials and methods used in a modelling and simulation-assisted biomimetic approach on the topic of anaerobic digestion (AD).

Use case presentation

Anaerobic digestion is a biological process in which microorganisms break down organic matter to produce biogas, a renewable energy source [19]. Current digesters offer satisfactory performances, but remain optimisable, as they encounter problems of preferential pathways and dead volume amongst others. On average, 30% of the introduced matter is not recycled in valuable elements [20]. The best digesters (with the strongest yield) are in the living world, in the rumen of bovines. The rumen is a large, pouchlike fermentation chamber, divided into dorsal and ventral sacs by muscular folds. A student project was built around the topic of optimizing the anaerobic digestion process through the development of a biomimetic digester, inspired by the rumen of cows. Students were Master 1 engineering students from UniLaSalle with specialisations raging from geosciences to nutrition, to life-sciences and agronomy. The purpose of the project was to model and run simulations on both the biological model, a rumen, and a biomimetic version of an anaerobic digester, built with the learnings they gathered from the rumen model.

Use case set up

Students had two weeks to build the models, run the simulations, and come up with a biomimetic digester. Their progression was guided by the design thinking framework. To narrow down the scope of potential upgrades, students were asked to focus on the hydrodynamics, and so mostly worked with Computational Fluid Dynamics (CFD). Modelling was conducted using the Xgenerative design software in the CATIA suite. Simulations were run through Xflow, using the Large Eddy Simulation (LES) approach. The latter was selected for its high accuracy, despite its demand for substantial computational resources. The entry parameter was set to a constant speed, and the exit parameter to atmospheric pressure.

RESULTS

Biological model

In the modelling process, students aimed to remain as close as possible to the biological system. The overall shape and architecture were replicated: one big pouch, split into two pockets, dorsal and ventral. Both are visible on the figure below, the dorsal pouch is the top one, and the ventral pouch, the bottom one.

The rumen is submitted to different forces through muscle contraction and movement that aim to move the content of the rumen around (grass and other elements eaten by the animal) so it can be digested by the bacterial mass. These movements also contribute to the physiological regurgitation of nutrition, which can then be chewed and salivated again, an action known as rumination. To model the rumination process, a circulation system was set up, which ensured proper breakdown of solid matter, and prevented congestion in potential dead volumes. Movement is induced through a pump, and reinjection is done by a pipe going from the ventral pouch to the dorsal pouch. The dorsal pouch is where solid matter is broken down and digested. To make sure that the solid matter stayed as long as digested in the dorsal pouch, and that no amount of it would fall and clog the papillae or the recirculation system in the ventral pouch, a narrow grid was built in. It is only once reduced to particles by the digestate, that former solid matter can fall into the lower pouch.

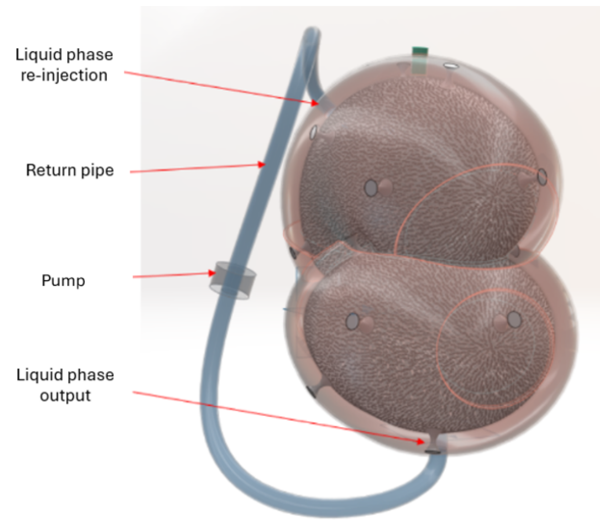

Figure 1a Biological model – a rumen

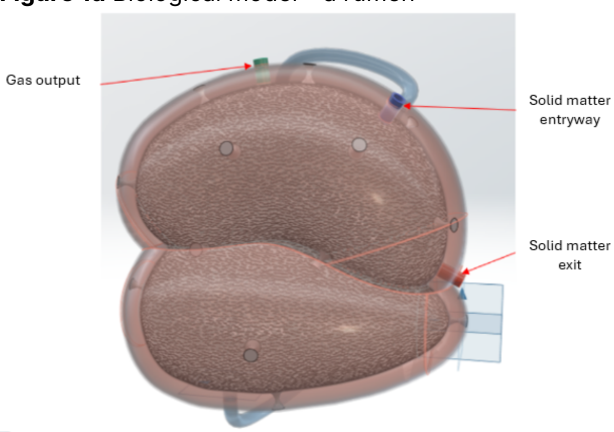

Figure 1b Biological model – a rumen

Rumen walls are lined on the inside with shaggy, tongue-like papillae that give it a textured, velvety appearance. Within the mindset of representing all components of the system, to be as reliable as possible in the visual but also functional representation, students integrated inner, smaller-scale structuration into their rendition.

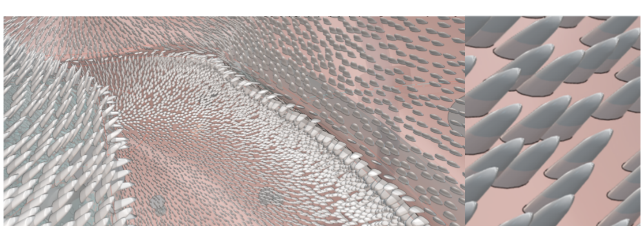

Figure 2 Inner wall layering in biological model

Biomimetic model

Anaerobic digestion can follow two main pathways depending on whether the handled feedstock is considered as solid or liquid. Solid-state digestion is built to manage unpumpable, and dry feedstock, where liquid-state digestion handles pumpable, slurry-like feedstock. Students observed CSTR solid and liquid-state digesters as reference systems to design the biomimetic versions. Both are of cylindrical shape, with the addition of a mixer for the liquid-state. Simulations were run to observe matter movement inside of traditional digesters. Below are the simulation results for the solid-state.

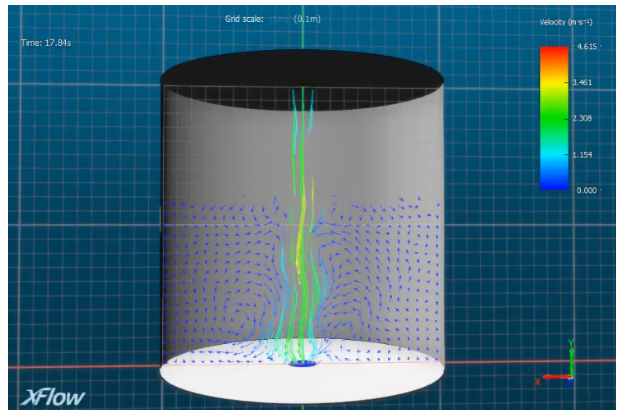

Figure 3 Solid-state digester fluid dynamic simulation Color gradient shows fluid velocity in $m.s^{-1}$

Fig. 3 simulates matter movement inside the solid-state digester. The first observation is that there is a definite preferential path to matter movement: a straight line from entry to exit points. The existence of a preferential path in the digester is not a desired effect. Moreover, the path visible here is the most direct one, and carries matter at a high speed (1.15 to 3.40 $m.s^{-1}$) which is not intended. Indeed, the objective is to have sufficient retention time in the digester to allow solid matter exposure with methanogenic bacteria. If the matter tends to go straight from entry to exist, in the fastest way through, retention time is not optimized. Also, if matter follows a preferential path, it means that the matter outside of this path gets stuck, creating dead weight, also an unwanted phenomenon.

Dead volume is the second observation that can be taken from this simulation result. The matter on the left and right of the preferential path moves very little, to not at all. Arrows on the graph do not indicate movement, and if so, only minimal and slow.

As displayed in Fig.4 below, the liquid-state digester also shows subpar fluid dynamics.

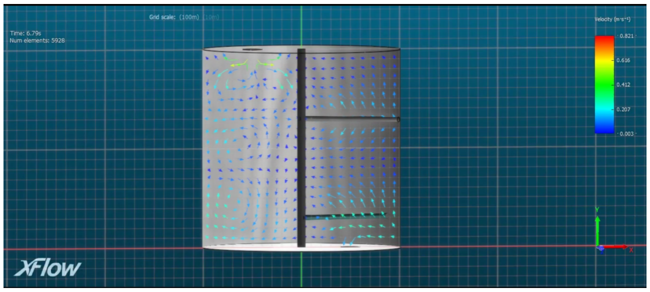

Figure 4 Liquid-state digester fluid dynamic simulation
Color gradient shows fluid velocity in m.s^{-1}

The action of the mixer ensures matter movement around the digester. It appears that matter is pushed around and sped up by the mixer into circle-like pathways. An observation that is worth underlining is that, compared to the solid-state digester, velocity around entry and exit point is not significantly bigger than in the rest of the digester, specifically at the exit point. This leads to wonder if matter is going through. Fig. leaves the question on the recirculation of matter in the digester. In the solid-state digester, the seemingly present issue was of too little retention time, but here, it might be of too big retention time. If feedstock doesn't get though, the bacteria could exhaust the needed molecules for methanogenesis, which would put a halt to production.

Two focus points can be extracted from the analysis of the non-biomimetic digesters: limiting dead volume, and preferential pathways and optimizing retention time.

The goal was then to build a biomimetic digester with improved hydrodynamics to deals with these issues. Students built two different systems for solid-state and liquid-state pathways and ran simulations of internal hydrodynamic flow. For both systems, the shape was designed as rumen-like, with two pockets (dorsal and ventral/upper and lower), and an oval architecture to avoid dead volumes, and allow the entire volume of the digester to be used effectively. Below are the simulation results for the solid-state biomimetic digester.

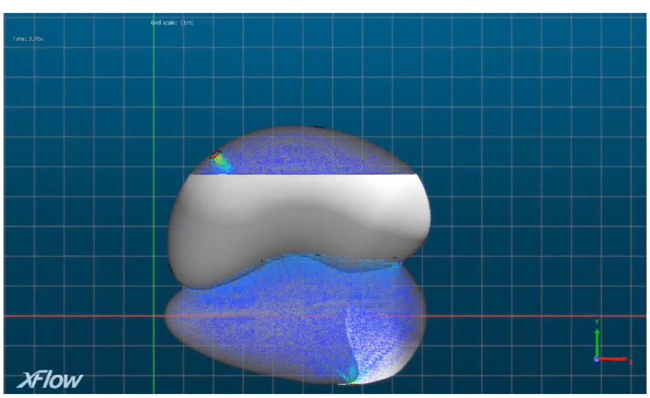

Figure 5a. Biomimetic solid-state digester fluid dynamics
Color gradient shows fluid velocity in m.s^{-1}

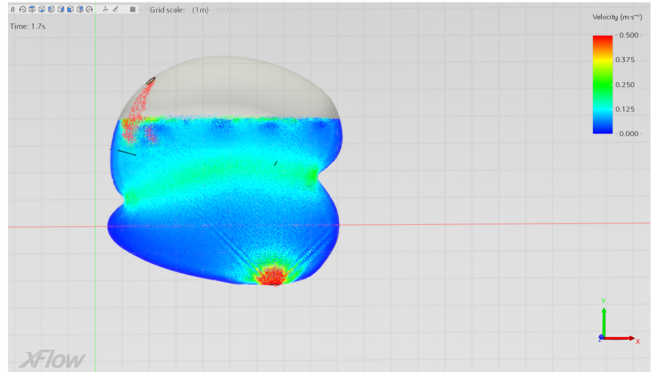

Figure 5b. Biomimetic solid-state digester fluid dynamics
Color gradient shows fluid velocity in m.s^{-1}

Fluid dynamic simulation in the biomimetic solid-state digester shows varying speed of matter inside of the system. The separation between dorsal and ventral pouches is a "fast-moving" spot with matter circulating around 0, 25 m.s^{-1}. It is worth noting that the acceleration occurs through the entire length of the separation and not specifically on one spot. It seems that matter is injected at high speed, slows down in the dorsal pouch, gradually speeds up going through the separating grid, and gradually slows down in the ventral pouch before being pushed out by overflow.

The following results were obtained for the liquid-state biomimetic digester.

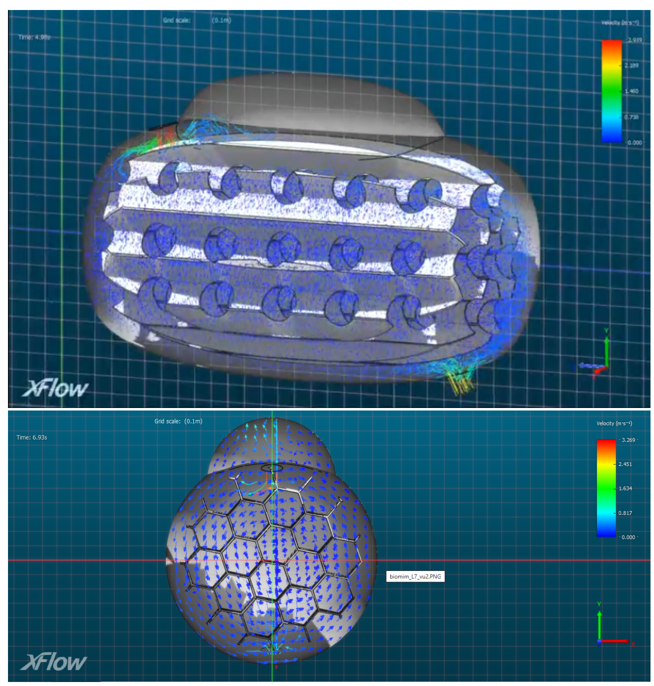

Figure 6. Biomimetic liquid-state digester fluid dynamics
Top figure : side view ; Bottom figure : front view
Color gradient shows fluid velocity in m.s^{-1}

The main takeaway from these results is that the redesign of the mixer and the overall shape of the digester are very beneficial to matter movement. Gas production is stored up in the superior pouch, and fluid simulations show the entire volume of matter circulating around all the available space. The light blue strands in Fig. indicate that once matter is introduced in the digester, it does not remain at top or bottom parts but goes through the hive-like mixer. Overall speed is relatively slow (0 to 0, 75 m/s), but movement is homogeneous, which is wished for.

To sum up, a model of a biological system, a rumen, was designed and underwent simulation testing to gather knowledge on its interior fluid dynamics. Fluid dynamics were also observed in non-biomimetic digesters in two pathways for anaerobic digestion: solid-state and liquid state. The analysis highlighted issues of preferential pathways and dead volume in the digester current design. The insights on the inner workings of the rumen, which stands at the top of the yield pyramid for methane production, were used to design biomimetic digesters, with the specific focus of hydrodynamic improvement. Initial simulations of the biomimetic systems show an upgrade in fluid circulation, and so a reduced tendency for preferential pathways and a minimization of dead volume.

Results are still preliminary and superficial and stand more as a qualitative validation of the overall improvement of digesters through a biomimetic approach. Additional data and testing are needed to push the biomimetic systems further. For example, it would be interesting to calculate retention time and biogas production in the biomimetic systems and compare them to the performances of current systems (non-biomimetic digesters). Another opportunity would be to dig deeper on the papillae structures that maximize absorption surface. It was not studied here as only hydrodynamics were of concern, but they remain an addition proposed by the biological system for the technical one and probably play a substantial role.

DISCUSSION

The central point argued in this paper is that biomimetics and modelling and simulation tools have the potential to work in a mutually reinforcing relationship. Recent works support and put forward arguments showcasing this synergy [5, 8, 14, 21].

On the one hand, the literature and the studied use case support that biomimetics can contribute to the development and improvement of modelling and simulation tools. Following a biomimetic approach indicates the study of biological systems, which are known as complex, multiscale, and multifunctional. This degree of intricate, hierarchal geometry stands on the current edge of the modelling and simulation capacities, despite recent improvements. It is only through these improvements that trying to model biological systems is conceivable, still, not yet easily feasible. The rumen use case discussed previously led to conclusions that support the positioning of biological models on the limit of what tools are currently able to model. Indeed, the design of the rumen pushed the software to its computational limits, specifically, in attempting to replicate the lining of rumen walls with papillae. Due to the sheer scale and number of required features, students were forced to model the papillae at a larger-than-natural scale to achieve convergence. This observation underlines that modelling and simulation tools need to improve in some way to compute and navigate such complexity (ie. multiscale structure). Ability to do so is essential as in biological systems, multiscale structure is often crucial to the performance of a specific function. So, biomimetics can contribute to the development of modelling and simulation tools by challenging them with the innate complexity of biological systems. For example, biology works with both hard and soft components to profit of their respective advantages (resistance, flexibility....), where engineering processes are focused on "hard materials" (steel, concrete...). Modelling biological systems could push the development and expand the versatility of Fluid-Structure Interaction (FSI) capabilities in software. In the presented use case, it would have been more accurate to represent rumen wall deformability and observe the influence of such capacity on fluid dynamics, but it was not feasible.

On the other hand, modelling and simulation tools could also bring beneficial elements to biomimetics.
Their integration to product development has increased product complexity, enabled early validation of performance, as well as quick and cheap iteration loops to test design options, and multicriteria analysis to identify the most suitable design alternative overall (finances, manufacturing capabilities, level of performance...). The biomimetic process would benefit from such additions as it faces struggles, notably related to the disruptiveness of the systems it leads to. This hypothesis opens the door to future work on the validation of mentioned benefits in the case of biomimetic design.

An essential part of the biomimetic process is transferring the principle of the biological function to the chosen field of application. If done poorly, it is likely that the resulting system will not deliver to expected levels. Proper transfer is deeply related to biological system understanding. Visual representations have always been used to describe, and comprehend the way systems, including living ones, function. Modelling and simulation tools lead to advanced visuals, gathering more information of the modelled system with the addition of one dimension (2D to 3D). A double hypothesis stands that through the standard use of modelling and simulation tools in biomimetic design, biological system understanding would be improved, and resulting biomimetic systems would meet expectations.

In the use case, without modelling and simulation tools, getting to a deep and intricate enough level of understanding of the rumen, and the fluids dynamics it holds, would have been extremely complicated, and vastly more expensive. Using a porthole cow would not have necessarily brought the needed data, on top of being an ethically questionable approach. Perhaps, required data could have been obtained through the ingestion and monitoring of movements, of a traceable sensor by a cow, but it remains a demanding experiment in terms of resources.

Going further than improving the understanding of systems of interest, models and simulations could help figure out the viability frame of biological strategies. As seen in the use case with papillae structures, biology often works at small scales (nano and micro). Being able to assess if the desired function is governed by scale, or other parameters, would be a game-changing ability. In the example, knowing if absorption improvements brought by structures like papillae are only present if said structures are of nano or microscale, is an extremely important fact. Indeed, it indicates that nano or micro texturation would be an essential element to the biomimetic system for it to be functional. Information that signals early-on future manufacturing constraints. A hypothesis is here that models and simulations, specifically parametric models, could assist in the determination of the viability frame of a function, thus informing on its usability by a specific actor, depending on the field of application and manufacturing capacities.

All hypotheses made above must be tested through rigorous experimentation. They stem from the authors reflexion around the relevance of biomimetics and modelling tools together but are not yet verified statements.

CONCLUSION

The aim of this article was to showcase the mutually beneficial relationship between biomimetics and modeling and simulation tools. The difficulty to model biological systems challenges modelling and simulation tools and stimulates their development and improvement to be able to cope with that level of complexity. Modelling and simulation tools are believed to be relevant to assist in a core step of biomimetics, which is the transfer of the biological function to the chosen field of application. This assistance would stem from the improvement of the understanding of biological systems through informative visuals. Parametric modelling could play a break-through role in determining the viability frame of biological functions, thus advising on biomimetic system feasibility. it is conceivable

Future work could focus on the experimental validation of the hypothesis around modelling and simulation tools for biomimetics, as well as on building the methodological steps needed to standardise the use of such tools in biomimetic design.

The end goal of such work is to facilitate the wider adoption of biomimetics as a problem-solving design approach, ultimately promoting the emergence of biomimetic innovations across diverse applications.

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